Available online at www.sciencedirect.com
ScienceDirect
Procedia Computer Science 96 (2016) 1609 – 1618
Procedia
Computer Science

20th International Conference on Knowledge Based and Intelligent Information and Engineering Systems

Formal models for intelligent speed validation and adaptation

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Abstract

This paper presents an approach for an intelligent speed validation and adaptation. The approach focuses on formal modelling of the corresponding smart vehicle units, to increase the road safety as well as to allow formal analysis of the smart vehicle behaviour. We suggest a number of models for speed check/limitation units, which reflect differences in the speed limits in several countries. We also present our results from the case studies, based on two implementations of the model as an iOS and an Android app for Intelligent Speed Adaptation.

Peer-review under responsibility of KES International
Keywords: Road Safety, Intelligent Vehicle, Transport system, Smart City

1. Introduction

The research on Intelligent Speed Adaptation (ISA) was initiated more than 30 years ago. A number of case studies have shown that ISA systems can contribute to the road safety. However, there are a number of questions how the ISA systems can be deployed in a large scale[1]. In general, the ISA systems can be divided into two categories: warning ISA systems and speed limitation systems built in the vehicles. The warning systems can be developed as a smartphone app, or as an additional functionality of a standard satellite navigation device, with or without connection to the vehicle's speedometer. The cheapest solution would be to calculate the speed of the vehicle based on the GPS signal, however the connection to the vehicle's speedometer might provide more accurate results. The built-in speed limitation units are more expensive to develop, and, what might be more critical, the public acceptance could be the obstacle to a large-scale deployment for this kind of ISA. On the modelling level, the core ISA functionality would be:

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Peer-review under responsibility of KES International
doi:10.1016/j.procs.2016.08.208

- to analyse the speed limit in the area the vehicle is driven,
- to compare the current speed with the speed limit, and
- to provide a warning message,
- to limit the speed automatically (optional).

In this paper, we introduce our approach on modelling the ISA systems. We propose a formal model of an intelligent vehicle that can be applied as a driver assistance application (DAA)[2] or be adapted for autonomous vehicles. The functionality of DAA can vary from just informing messages, or warning messages in critical situations (e.g., blind spot warning, line change detection, etc.) to giving full control to the vehicle (e.g., autonomous parking application, available today with many modern vehicles).

In our previous work[3], we presented a formal framework for modelling and analysis of autonomous systems and their compositions, especially focusing on the adaptivity modelling aspects and reasoning about adaptive behaviour. In[4] we presented an approach towards intelligent route planning in public transport systems, with the focus on formal modelling of the semi-dynamic intelligent route planning and optimisation. Our current work continues the above mentioned research, focusing on speed-limit analysis and checks for autonomous systems and their compositions. We elaborated a formal model covering real-time and space aspects, based on FocusST modelling language[5]. FocusST was inspired by Focus[6,7], a framework for formal specification and development of interactive systems. The syntax of FocusST language covers specification of spatial (S) and timing (T) aspects, which is the reason to extend the name of the language by ST. The specification layout in FocusST is based on human factor analysis within formal methods[8,9].

Intelligent speed validators can make the transport system safer and easier to use. As per statistics presented by Dhillon[10], 80% to 90% of the errors in aviation and traffic accidents were due to human error. By the integration of human factors engineering into the development process, we can improve the quality of software and system in general as well as deal with human errors in a systematic way[11].

In the rest of the paper, we will emphasise the development of formal models for an intelligent route planning for intelligent speed check units.

Outline: The rest of the paper is organised as follows. In Section 2 we discuss the related work. Section 3 provides a short description of spatial aspects modelling in FocusST. In Section 4, we discuss two models for intelligent speed validation and adaptation. Section 5 introduces our ongoing case studies at the RMIT University. Section 6 concludes the paper by highlighting the main contributions and introduces the future work directions.

2. Related Work

Adaptive Cruise Control (ACC) systems were developed to extend the speed keeping function by automatic distance keeping. However, as the presented by Nilsson study[12], the read safety may be negatively influenced by ACC systems, because the drivers sometimes expect from ACC systems more functionality than is actually provided, which leads to the reaction delays in critical situations. On the other hand, this study[12] also demonstrated that early system actions and warning may reduce criticality. Thus, the major problem detected by this study was not on ACC functionality, but on the level of interaction between human and machine, i.e., on the level of human factors engineering and human-computer interaction.

Feilkas et al.[13,14] introduced a top-down methodology for the development of automotive software, which was evaluated by developing an ACC system with Pre-Crash Safety (PCS) functionality.

Young et al.[15] presented a design solution of a novel mobile robot navigation system, to control robot's locomotion across slippery surfaces. Leung et al.[16] presented a path planning approach for Micro Aerial Vehicles in urban environments.

Lahrmann et al.[17] analysed the results of a research project at Aalborg University in Denmark. The goal of the project was to develop an Intelligent Speed Adaptation (ISA) system. The system was tested by 24 test drivers to collect users' reactions to the system.

Vlassenroot et al.[18] presented results of ISA trial, held in Belgium from 2002 until 2004. Within the trial, 34 cars and 3 buses were equipped with an ISA-system with the goal to study how does the ISA influence on road safety, behaviour of drivers, etc. According to the presented results[18], (1) ISA can have benefits in road safety, (2) the drivers declared that ISA is most useful in lower speed-areas, but observed driving behaviour shown the opposite (the drivers were still driving to fast in 30 km/h areas).

Another ISA trial, held in UK between 2004 and 2006, was presented by Lai and Carsten[19]. The trial presented an evidence on how drivers' choice of speed is altered. Lai and Carsten mentioned, that the use of ISA system had distinctive effect in terms of transforming the speed distribution across all speed zones except the 60 mph zones. The authors also highlight that, based on the trial results, "*ISA demonstrates a very large potential for safety benefits, considering the strong relationships between speed and accident occurrence as well as severity*".

Warner and Åberg conducted a study[20] to analyse drivers' speeding behaviour after long-term use of an ISA speed-warning device. The study demonstrated that the average time of driving above the speed limit greatly decreased when the warning system was activated. Chorlton and Conner[21] also conducted a study to determine the impact of long-term experience with ISA on drivers' cognitions, which validated the point that intentions to speed were became significantly weaken following long-term experience with the ISA system. Another study[22] conducted by Warner and Åberg was focused on analysis of drivers' beliefs about exceeding the speed limits.

On the automobile autonomy levels scale, given in Elbanhawi et al.[23], where the level 0 means *no autonomy* at all and the level 4 refers to *full-self-driving*, ISA is placed at the level 1, known as *function specific*. Vehicle taking control and slowing down in the emergency situations, is the first step towards loss the of controllability. That will probably increase the susceptibility to motion sickness. This is now subject of an intensive research that involves large number of volunteer drivers, conducted at RMIT University. It involves electrophysiological monitoring, using Electroencephalography (EEG) data, as a method to record electrical activity of the brain, while driver is exposed to the loss of controllability consequences.

3. Spatial Aspects in FocusST

FocusST specifications are based on the notion of *streams*, where a stream is defined as a mapping from the set to natural numbers $\mathbb{N}$ to lists of messages within the corresponding time intervals. To avoid the omission of crucial assumptions about the system's environment, every component is specified using assumption-guarantee-structured templates (a specified component is required to fulfil the guarantee only if its environment behaves in accordance with the specified assumption).

A FocusST specification can be seen as a special kind of timed automata, *Timed State Transition Diagrams* (TSTDs)[5,24]. A TSTD can be described in both diagram and textual form. For easier argumentation, we can further represent it by a special kind of tables including a number of new operators that work on time intervals. For a real-time system S with a syntactic interface $(I_S \rhd O_S)$, where I_S and O_S are sets of timed input and output streams respectively, a TSTD corresponds to a tuple $(State, state_0, I_S, O_S, \rightarrow)$, in which $State$ is a set of states, $state_0 \in State$ is the initial state, and $\rightarrow \subseteq (State \times I_S \times State \times O_S)$ represents the transition function of the TSTD.

An input action for a TSTD is the set of current time intervals of the input streams of the system, while the output action is the set of corresponding time intervals of the output streams of the system. We defined[5] a special type of components specifying real objects that can physically change their location in space, so-called *sp-objects*. Each sp-object is associated with three attributes (special kind of variables) storing its current *location* (i.e., central point of the object), *speed* and *direction* of movement. For simplicity, the variable *speed* is defined over the set of natural numbers $\mathbb{N}$, while *location* is of type $Space$ and defines a coordinate having two or tree dimensions according to the system's needs. In our two-dimensional example, *Space* is a tuple of two Cartesian coordinates x and y. Finally, *direction* is defined over the type *Directions* $= \{0, \dots, 359\}$ which represents the angle in the Cartesian coordinate system. The variables *location*, *speed* and *direction* are defined globally for the system. They can be used to specify physical interaction of components in a system. Thus, a system model is constrained by restricting the directions and speed of an sp-object. This allows us to verify whether the specified behaviour excludes the possibility that the object enters restricted areas during time intervals marked as dangerous, e.g., collisions with other sp-objects.

4. Model of an intelligent speed validator

To model speed check/validation, we have to add the corresponding constrains to the basic FocusST model. The speed limitation depends only on the area/route the vehicle is driven, i.e., the spatial aspects have to be taken into account in all cases. However, in some cases we also have to take into account timing aspects such as time of the day/night and calendar date, e.g., in many countries additional speed limits apply within the school zones during the school time. In Australia (Victoria) is 40km/h during the school days, between 8am and 9:30am, as well as between 2:30pm and 4pm (let us name these times *school transport time*). Moreover, the type of the vehicle should be also taken into account. For example, in Germany a general speed limit for trucks with a gross vehicle weight rating (GVWR)[1] over 3,500 kg is of 80 km/h, where for vehicles with a GVWR of over 7,500 kg the limit is set to 60 km/h. We could specify the corresponding data type as

$$\mathsf{type}\ VehicleType = \{Motorcycle, Auto, Truck\}$$

Thus, we have to take into account many aspects describing the vehicle and the route, e.g.,

- country (each country has different speed limits);
- type of the vehicle;
- type of area, such as
  - school zones or other zones that are with speed limits depending on time/date,
  - town (built-up) areas (areas with general limits),
  - local area with a speed limit lower that general one,
  - rural area,
  - highest speed zone,
  - etc.

To apply FocusST for the vehicle speed validation and adaptation, we need to introduce two additional attributes for *sp-objects*: *vType* (representing the type of the vehicle) and *tSpeed* (representing the current speed limit for the object). Thus, each sp-objects will have five attributes associated with: *location*, *speed*, *direction*, *vType*, and *limSpeed*.

Let us discuss a simplified example, presented on Figure 1. There are two sample routes depicted on the Figure 1, $A_1 \rightarrow A_2$ (vehicle moves from point A_1 to point A_2) and $B_1 \rightarrow B_2$ (vehicle moves from point B_1 to point B_2). We use the following notation:

- **blue areas:** town (built-up) areas, i.e., the areas with general limits for towns (50km/h for Australia, Victoria);
- **dark green areas:** areas with speed limit 40 km/h;
- **light green areas:** school zones with speed limits depending on time/date, i.e., during the school transport time these areas can be seen as areas marked *dark green* with a speed limit of 40km/h, where out of these times these areas can be seen as *blue areas* with a general speed limit of 50km/h;
- **yellow areas:** areas with speed limit 20 km/h;
- **dash lines:** sample routes (in the presented scenarios, $A_1 \rightarrow A_2$ and $B_1 \rightarrow B_2$);
- **orange circles:** points where the vehicle should change (limit) the speeds, according to the presented scenarios.

To check for the speed limit, we could apply two following approaches:

- *Maps approach:* Information about the location of the speed signs is auxiliary and can be omitted on the map, the vehicle speed is adjusted according to the map "colouring" for the current location of the vehicle. In the Maps approach, we have to create a mapping from current location, time and vehicle type to the corresponding speed limit:

  $$SetLocalLimit : Space \times \mathbb{N} \times VehicleType \times TimeRestrictionType \rightarrow \mathbb{N}$$

  Based on the *SetLocalLimit* mapping, we can identify to which part of the route the current location of the vehicle belongs, and compare the current speed with the value of the speed limit variable *limSpeed*, adjusting it with the limitations based on the type of the vehicle.
  Advantage of the approach: Trivial calculations of the current speed limit for the vehicle.

[1] The maximum operating weight/mass of a vehicle.

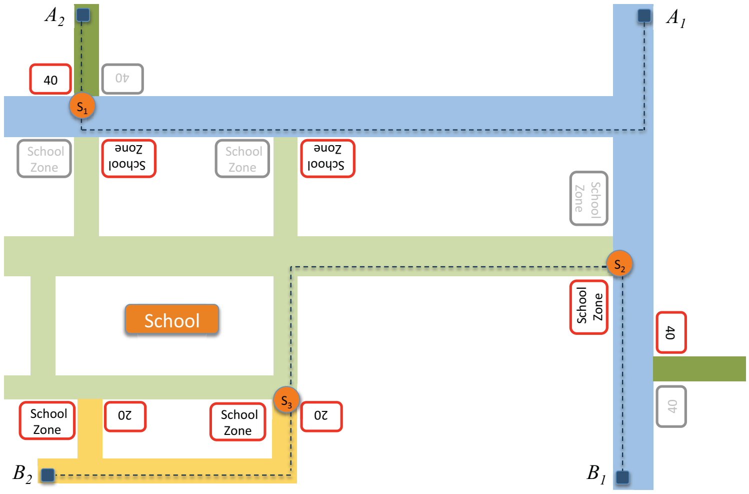


Fig. 1. Simplified example of a route map

Disadvantage of the approach: To store the *SetLocalLimit* mapping could be very resource consuming.

- *Markers approach:* The location of the speed signs is the basis for calculation of the current speed limit: the current speed limit has to be equal to the last approached speed sign (pointed in the direction of the movement). The colouring of the map can be omitted. We have to specify a data base representing the information on speed limit signs. In FocusST we define it as a final list *SpeedSigns* of the elements of a tuple data type (representing location and direction of the sign, as well as whether the sign is defined only for a specific kinds of vehicles and or specific time intervals).

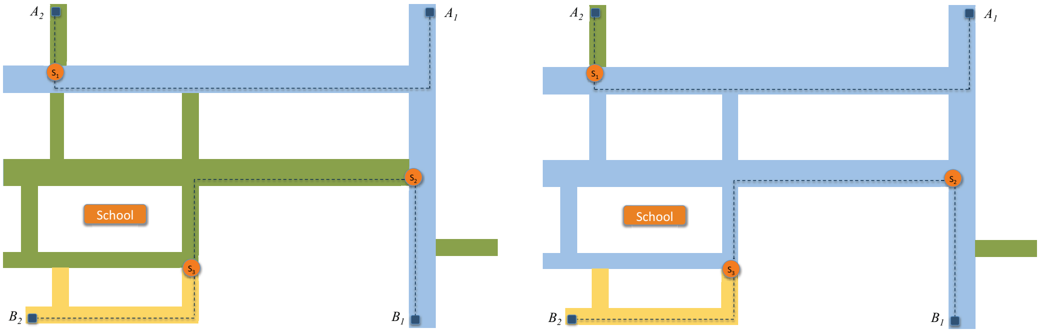
$$\textsf{type } SpeedSignsType = Space \times Direction \times VehicleType \times TimeLimitType \times \mathbb{N}$$

On this basis, we can calculate the value of the *limSpeed* variable for the next time unit $t + 1$ (denoted by $limSpeed'$):

$$\begin{array}{l} limSpeed' = \\ \quad \textsf{if } \exists\, tl \in TimeLimitType, lim \in \mathbb{N}. \\ \qquad t \in tl \wedge (location, direction, vType, tl, lim) \in SpeedSigns \\ \quad \textsf{then } lim \\ \quad \textsf{else } limSpeed \\ \quad \textsf{fi} \end{array}$$

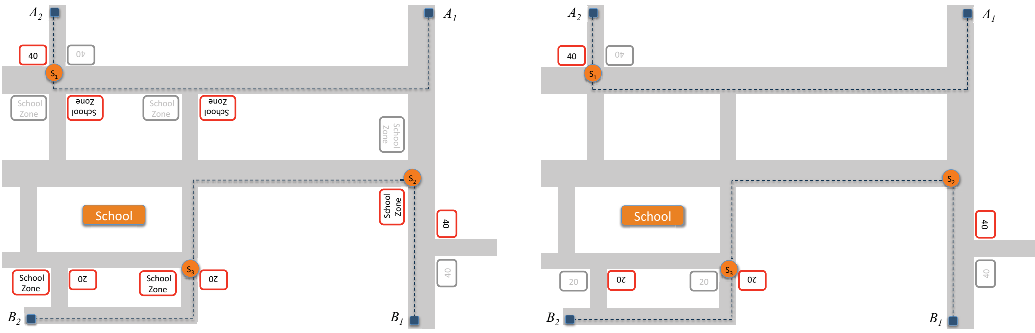
Thus, the value should be either updated in the case when vehicle is approaching an applicable sign (based on the direction of movement, type of vehicle, etc.), or still unchanged. Then, we have to compare the current speed with the limit, adjusting it with the limitations based on the type of the vehicle.
Advantage of the approach: Less resource consuming, more flexible. The data base *SpeedSigns* is much smaller than the mapping *SetLocalLimit*, as we need to store the information not about each possible location on the route, but only about a very small subset of locations, representing the speed limit signs.
Disadvantage of the approach: More complicated to identify the initial speed limit.

If a map includes zones with speed limits depending on time/date, we can see it as a set of maps with different colouring (for the Maps approach) or different sets of signs (for Markers approach). Thus, for the example from Figure 1, we would have a set of two maps, representing the limits within and out of school transport time. In the Maps approach the colouring of the route areas differ, cf. Figure 2. In the Markers approach some signs become invalid or should be replaced by other signs out of predefined time intervals, cf. Figure 3.



(a) within school transport time (b) out of school transport time

Fig. 2. Maps approach: Colouring of maps that include zones with speed limits depending on time/date



(a) within school transport time (b) out of school transport time

Fig. 3. Markers approach: Speed limit signs on maps that include zones with speed limits depending on time/date

Sample route $A_1 \rightarrow A_2$: The speed limits for this sample route do not depend on the date and time. The vehicle moves through the area with a general limit of 50 km/h from point A_1 to the first intersection, turns right to follow through the area with a general limit till the next right turn, then turns right to the area with a speed limit 40km/h (speed-change point S_1) and stops at point A_2.

Sample route $B_1 \rightarrow B_2$: The speed limit depend on the date and time, when the vehicle moves between points S_2 and S_3 on this route.

Scenario for school transport time: The vehicle moves through the area with a general limit of 50 km/h from point B_1 to point S_2, turns left adjusting the speed to the limit of 40km/h, moves till the first left turn, turns left and moves to point S_3, where the speed has to be adjusted to 20km/h, turns right at the end of the street and moves till point B_2 is reached.

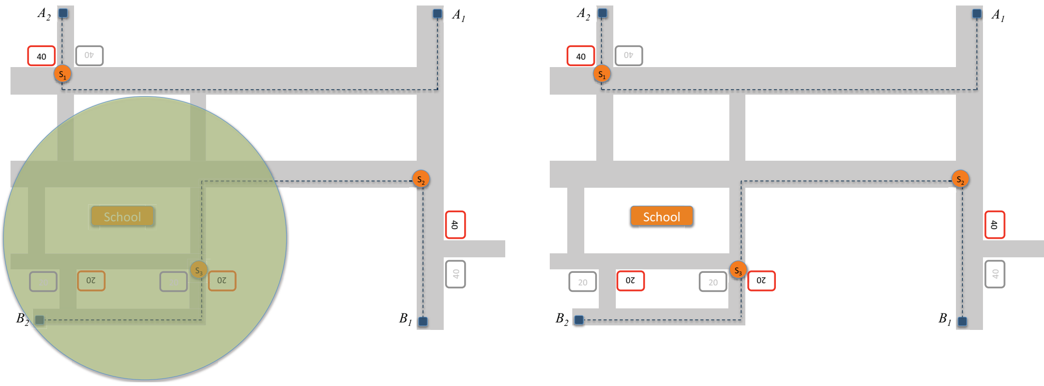
Scenario for a time out of school transport time: The vehicle moves trough the area with a general limit of 50 km/h from point B_1 to point S_2, turns left and moves till the first left turn, turns left and moves to point S_3, where the speed has to be adjusted to 20km/h, turns right at the end of the street and moves till point B_2 is reached.

The Markers approach can also be modified, to optimise the analysis of the speed limits for specific areas. For example, in the case of school zones, an Intelligent Speed Adaptation system might calculate the corresponding speed limits based on the locations of the schools instead of the locations of the denoting a school zone speed signs. This optimisation would not provide us exactly the same notifications and adaptation schema, but it is more flexible to use and to implement. This allows us to optimise the data base *SpeedSigns* by removing the corresponding speed limit signs. Moreover, if the timing restrictions for the speed limits are valid for these kinds of areas only, we might also simplify the definition of the *SpeedSignsType* as follows

$$\text{type } \mathit{SpeedSignsType} = \mathit{Space} \times \mathit{Direction} \times \mathit{VehicleType}$$

Instead of this we have to use another (smaller) data base to store locations of the schools and a distance on which the notification about a school zone has to be provided to the driver. In FocusST we define it as a final list *SchoolLocations* of the elements of a tuple data type $\mathit{Space} \times \mathbb{N}$ (location and the distance). The information about timing restrictions has to be stored in a global variable *SchoolTRestriction* of the type *TimeRestrictionType*. This would provide us a model presented in Figure 4. The speed limits from the *SpeedSigns* should have higher priority than the limits calculated from *SchoolLocations*. For example, the 20 km/h signs should have higher priority than the limits calculated based on the distance from the school, cf. Figure 4.

In the next section, we discuss a case study where we implement the optimised Markers approach.



(a) within school transport time (b) out of school transport time

Fig. 4. Markers approach optimised for school zones

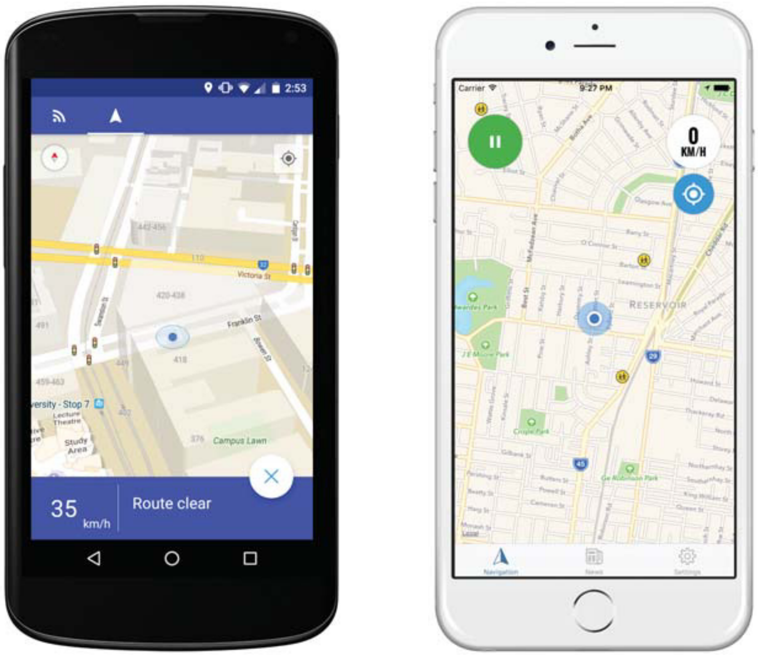
5. Case study: DriveVictoria

In this section we present two driver assistance applications that implement our model (based on the Markers approach) as an Android and an iOS apps. Both apps were developed within the Postgraduate Software Engineering Projects at the School of Science (Computer Science and IT) of the RMIT University. The apps are named *DriveVictoria*, as the case study was based on the information about the locations of the speed signs and the schools in Victoria. The corresponding data sets are accessible via VicRoads[2], the road and traffic authority in the state of Victoria, Australia, as well as Victorian Government open data[3].

Information about locations of the speed limit signs and schools is stored in a MYSQL data base on the server cloud, with each school information containing a pair of latitude and longitude indicating the position of the school and other information such as school name, address etc. When the *Driving Mode* of the app is on, cf. Figure 5, the app monitors changes in the GPS location of the vehicle, sends the new location (longitude and latitude) to the server.

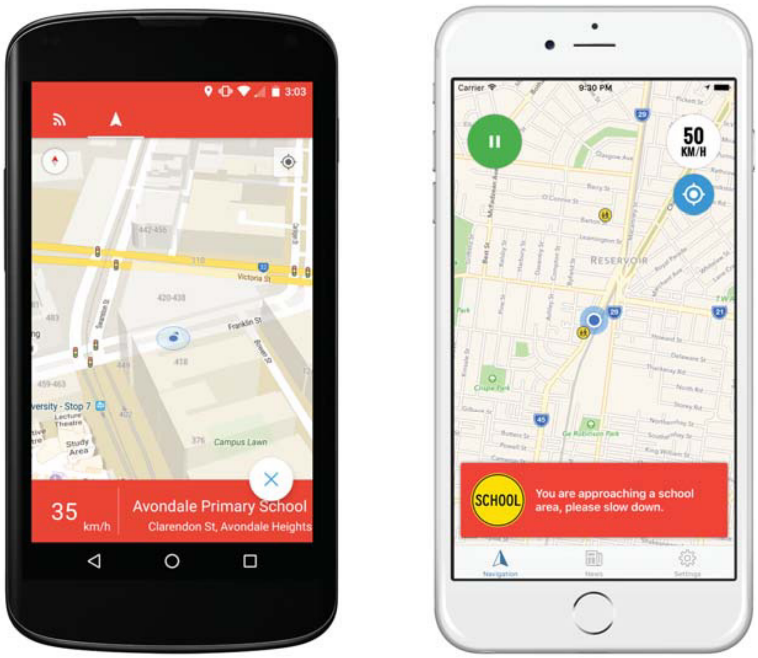
Based on the location of the vehicle and the current time (if the current time is within the school transport times), the server routine calculates the distance to school that is the nearest to the vehicle. In the current version, a default radius of 200 meters is defined to determine whether the vehicle is within the school zone. Thus, when the distance is less than 200 meters, (1) a notification message is sent to the app, and (2) the school information will be recorded at runtime to prevent a repeat notification for the same school. When the app receives a school zone notification message from the server, it provides a voice notification to the driver, the corresponding message is also presented on the screen, cf. Figure 6.

[2] https://www.vicroads.vic.gov.au
[3] https://www.data.vic.gov.au/



(a) Andriod app (b) iOS app

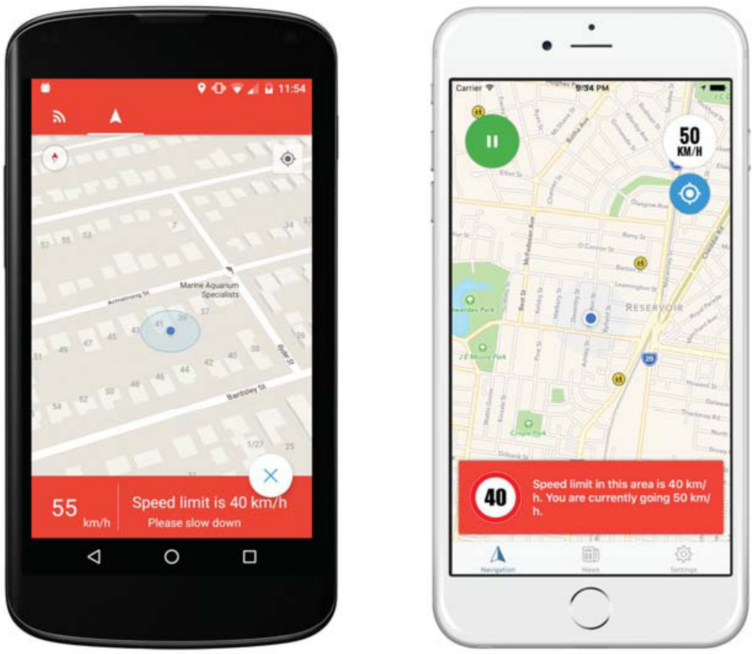
Fig. 5. DriveVictoria: Driving mode is on



(a) Andriod app (b) iOS app

Fig. 6. DriveVictoria: School Zone Warning

The value of *limSpeed* is calculated also on the server side, based on the information on the speed limit sings. When the current speed of the vehicle is above the current value of *limSpeed*, the app also provides a voice notification to the driver. The speed reminding message is also presented on the screen, cf. Figure 7.



(a) Andriod app (b) iOS app

Fig. 7. DriveVictoria: Driving above the speed limit warning

6. Conclusion

Intelligent Speed Adaptation (ISA) system is a step in the transportation systems transition from fully controlled vehicle by the driver, to fully autonomous driving where the vehicle itself is the intelligent subject on the road. Even with this small change in driving practice, there are number of issues in psychological and human physical domains. Regardless of that, many, if not all newly designed passenger vehicles, have certain level of intelligence, on that line, already implemented. Research presented here is extremely important for the large number of the drivers of the vehicles that are already on the road. They can use benefits of the intelligent technologies without need to invest large sums of money into new cars. The more we use this powerful technology, more feedback we will have, and more human lives will be saved. We have used powerful FocusST framework and readily available and assessable hands held devices to develop and test an driver assistance application.

Future Work: We will further expand research activities on other driver assistance needs like line change, line keeping, blind spot warning, warning about other vehicles on the road not behaving safely and other. Finally, moral, ethical, legal, social and other issues arising from the systems going up to the higher levels of autonomy, will be comprehensively investigated. Another possible direction of our future work is modelling of human behaviour in the context of proposed ISA, focusing on drivers' decision making analysis an role of emotions, e.g., following the approach proposed by of Vaa[25].

Acknowledgements

We would like to thank Peter Macpherson (Infringement Management and Enforcement Services Department of Justice and Regulation, Victoria, Australia) for valuable discussions on the subject of this research and on the core ISA features implemented as a case study within the Postgraduate Software Engineering Project.

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